Evaluating thermal and mechanical properties of composite films for EUV pellicle applications

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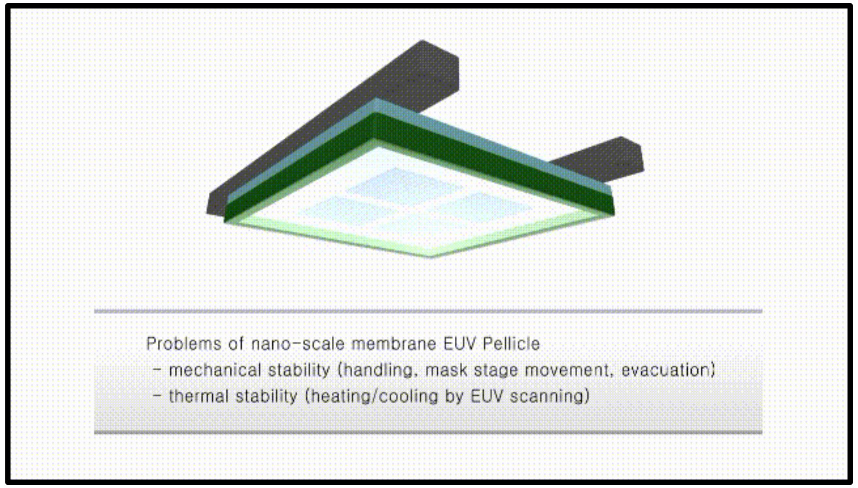
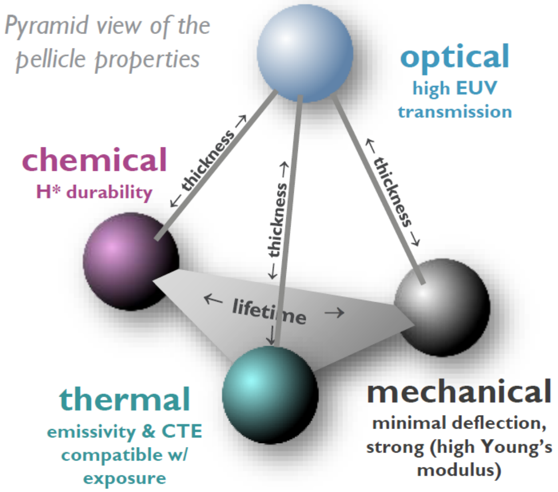
EUV Pellicle requirements

- Pellicle is a dust cover preventing particles and contaminants from falling on the mask



	Item	Requirement
Pellicle material requirements	Pellicle film EUV transmission	90% single pass (81% double pass) Product pellicle release transmission: >88% single pass
	EUV transmission spatial non-uniformity	< 0.4% Half range
	EUV transmission angular non-uniformity	< 300 mrad max. local pellicle angle
	EUV intensity in scanning slit @ pellicle	5 W/cm² (250W EUV source equivalent)
	Lifetime	under investigation
Pellicle + frame requirements	Standoff distance during exposure	2.5 mm
	Max. acceleration	100 m/s² during scanning
	Max. ambient pressure rate of change	Pressure gradient according to LDLK curve Film: deflection at 2Pa dP < 0.5 mm
	Reticle reserved area for pellicle assembly (centered on substrate)	See drawings



- Thin film of Si materials with high EUV transmittance is most promising candidate of EUV pellicle
- However, composite membrane is needed due to weak mechanical/thermal durability of Si materials

Ref. D. Brouns, IEUVI pellicle TWG meetings (2016) , I. Pollentier et. al, IEUVI pellicle TWG meetings (2017)

Proposal of EUV pellicle composite

❖ **Mechanical durability**

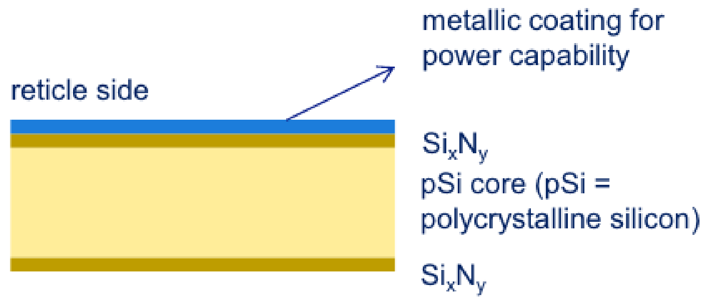
- ➢ Acceleration of mask stage (~100 m/s^2)
- ➢ Flow differences during pump down/venting process

❖ **Thermal durability**

- ➢ Heat load absorbed by pellicle membrane depending on EUV source power

	Target specifications			
	Product Phase	Transmission	Transmission non-uniformity	Power capability
Pellicle film generations	Pilot	>80%	1%	>125W
	Product	88%	0.4%	250W
	Future	≥90%	0.4%	>250W

Ref. P. Janssen et. al, IEUVI TWG pellicle (2016)



Core layer (Si materials) + Capping layer

EUV Pellicle requirements

- **Mechanical durability**
  - Acceleration of mask stage (~100 m/s^2)
  - Flow differences during pump down/venting process
- **Thermal durability**
  - Heat load absorbed by pellicle membrane depending on EUV source power

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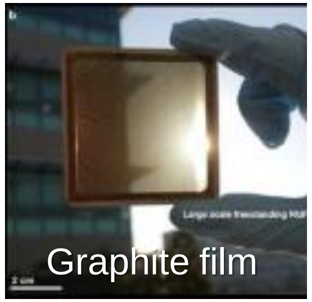
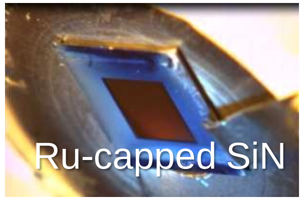
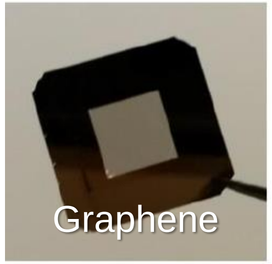
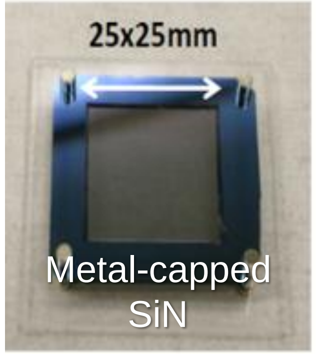
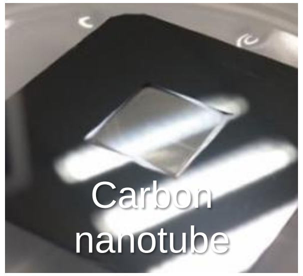
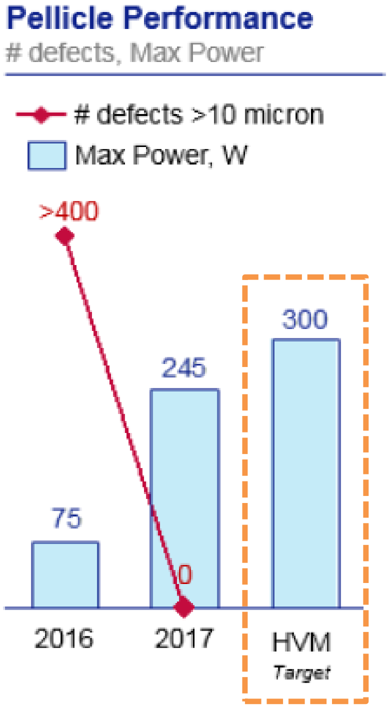












- **EUV pellicle should have thermal durability over 300W EUV source power to satisfy HVM target**
- **It is necessary to evaluate mechanical/thermal properties of various pellicle composite**

Ref. P. Janssen et. al, 2015 EUVL symposium (2015), S. W. Kwon et. al, IEUVI TWG pellicle (2015)
D. L. Goldfarb, IEUVI TWG pellicle (2017), I. Pollentier et. al, 2016 SPIE (2016) R. Van Es et. al, Proc. of SPIE (2018)

1. Introduction

2. Sample preparation & evaluation methods

3. Evaluation results of EUV pellicle composite based on SiN_x

4. Summary

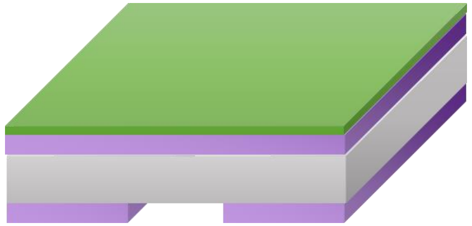
Fabrication of SiN_x composite membrane

SiN_x deposition & patterning

- **Low pressure chemical vapor deposition (LPCVD)**
- **Reactive ion etching**

Composite layer deposition

- **Transfer – CNT**



- **Sputtering – Ru**

Wet etching

- **KOH wet etching**
- **Rinsing (DI water + IPA)**

Substrate | SiN_x | Reinforcing layer | Thermal emission layer

❖ **Reinforcing layer**

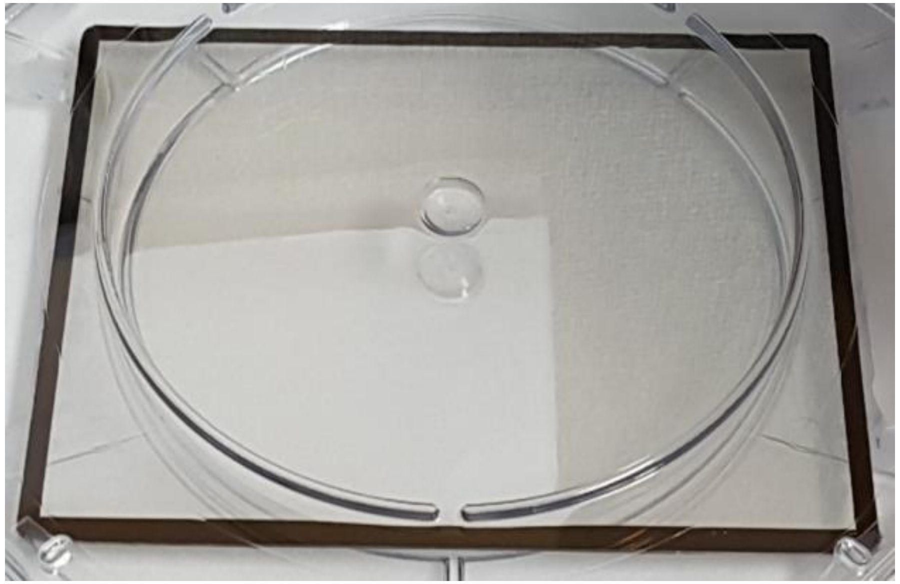
➢ Carbon nanotube (CNT)

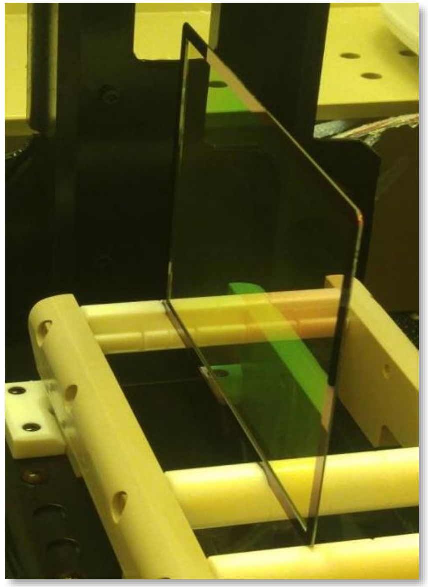
❖ **Thermal emission layer**

➢ Ruthenium (Ru)

Fabrication of full-size SiN_x pellicle

Full-size SiN_x pellicle membrane





Parameter	Value
EUV transmittance	83%
Thickness	34 nm
Pellicle window size	144 X 110 mm^2
Pellicle frame size	3.5 mm

- Full-size EUV pellicle based on silicon nitride was completely fabricated
- Full-size pellicle composite including thermal emission and mechanical reinforcing layer will be fabricated

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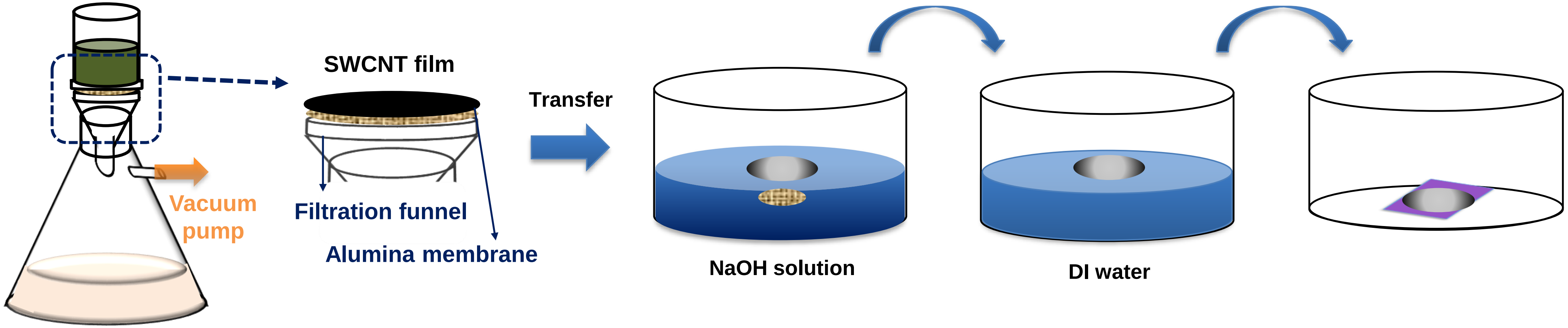
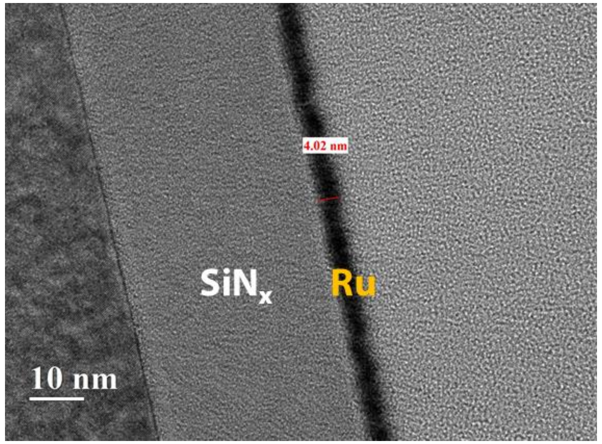
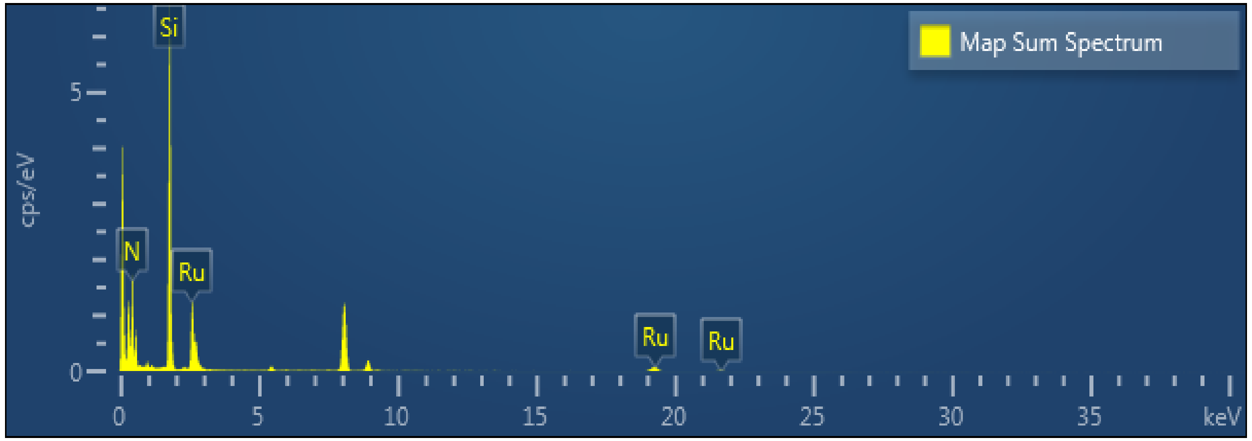
Composite layer deposition process

❖ Carbon nanotube (CNT) transfer



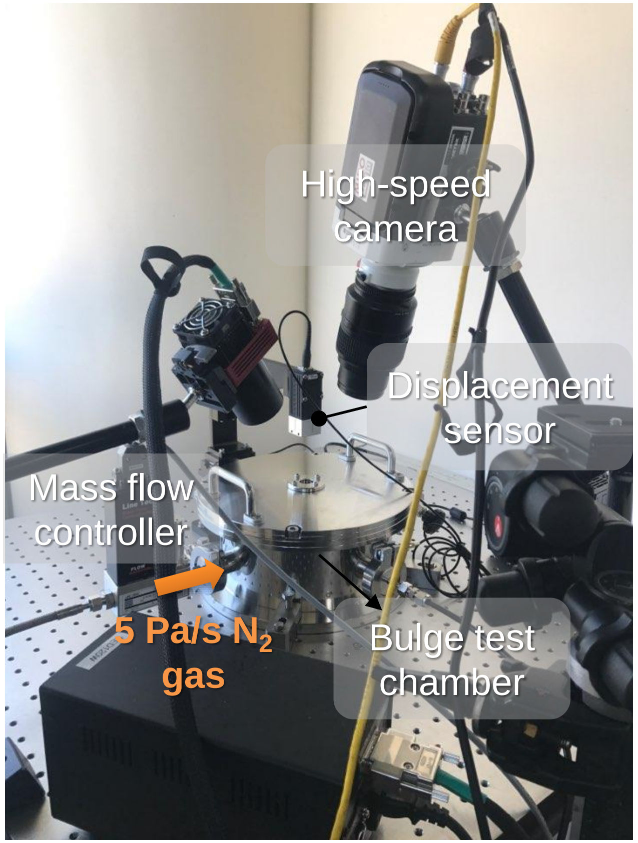
❖ Ruthenium (Ru) deposition - sputtering



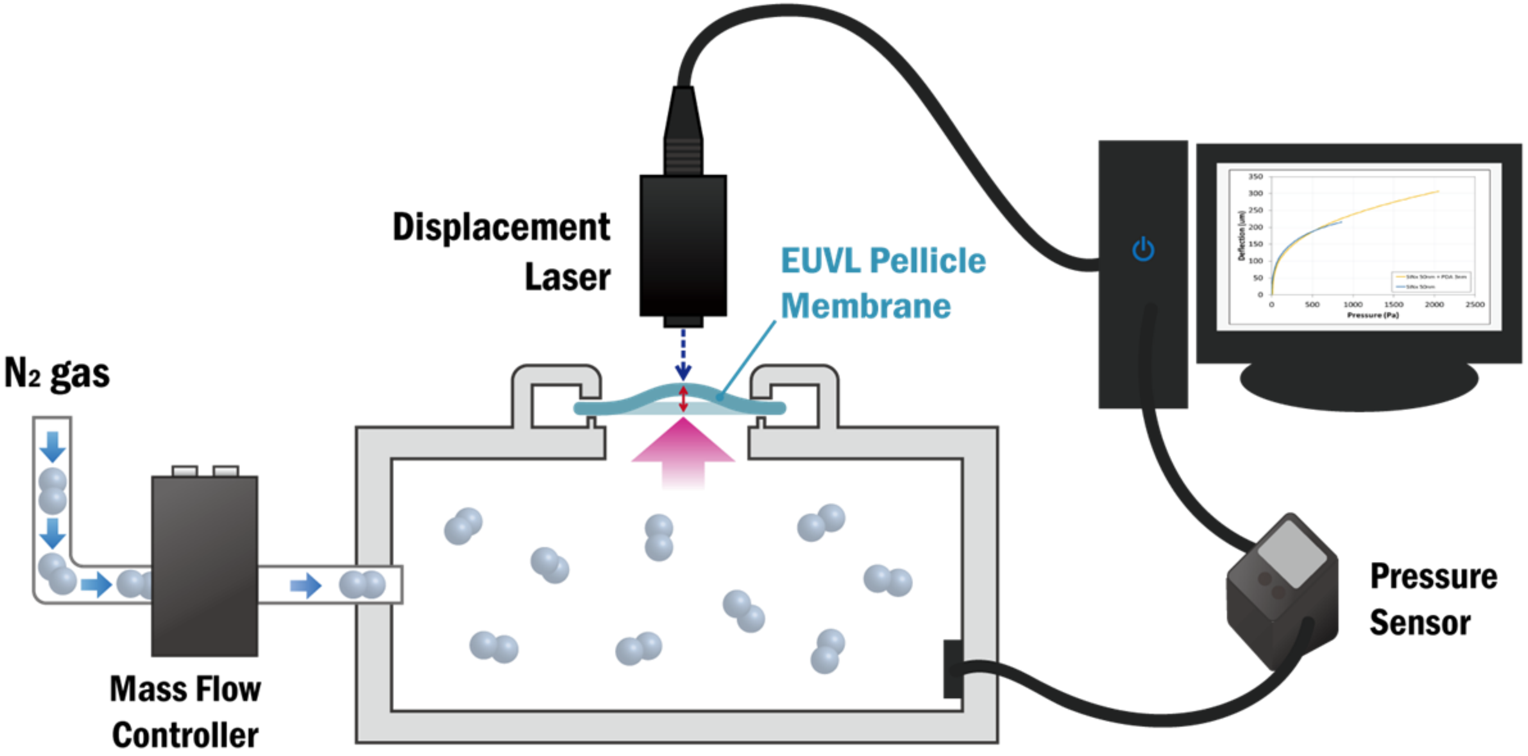


Bulge test equipment

Overview



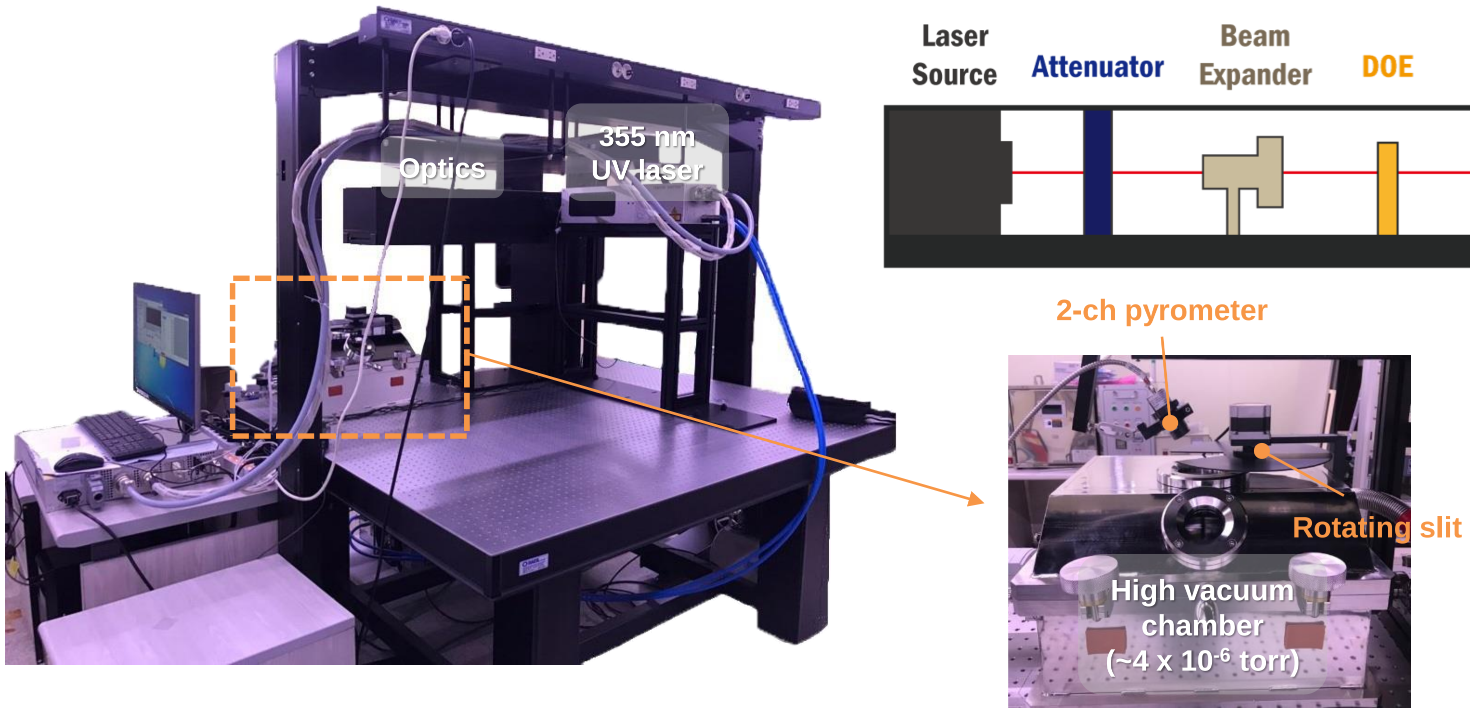
Schematic



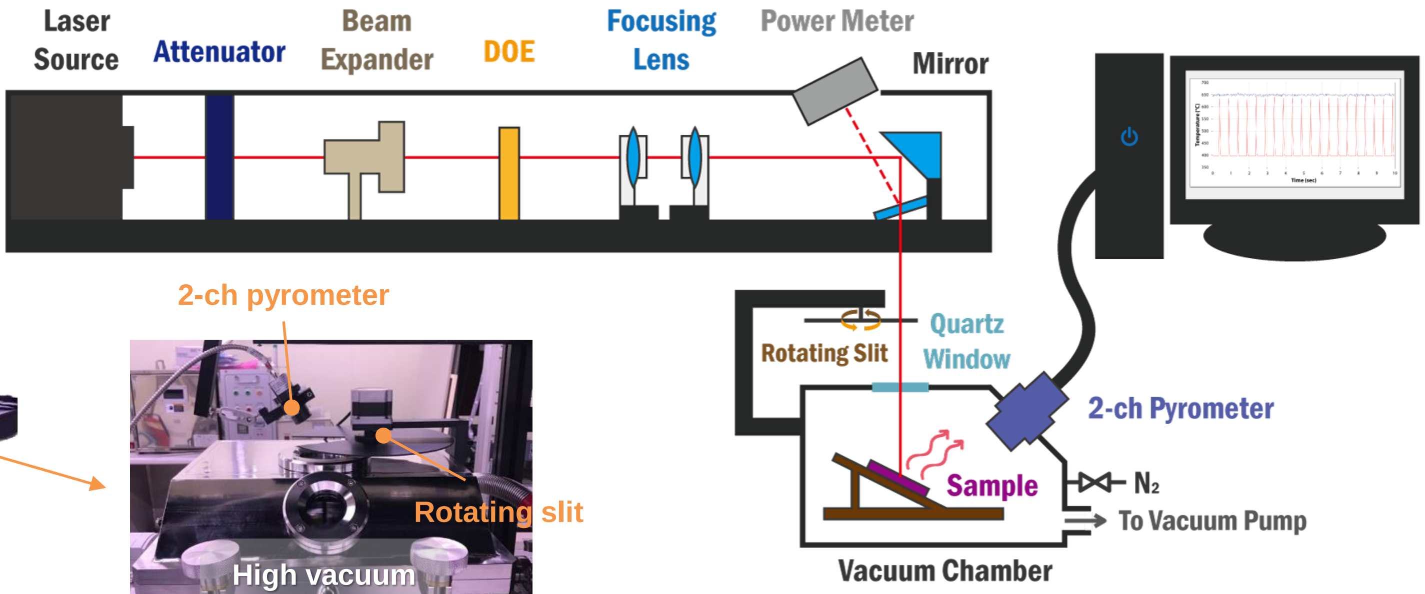
- Relatively simple method to evaluate mechanical properties of free-standing membrane
- Fracture point could be captured through high-speed camera

Heat load test equipment

Overview



Schematic



- Thermal properties of EUV pellicle can be evaluated by 355 nm UV laser
- Heat load of EUV pellicle in EUV scanner can be emulated by UV laser considering absorbance of membrane, high vacuum chamber and rotating slit

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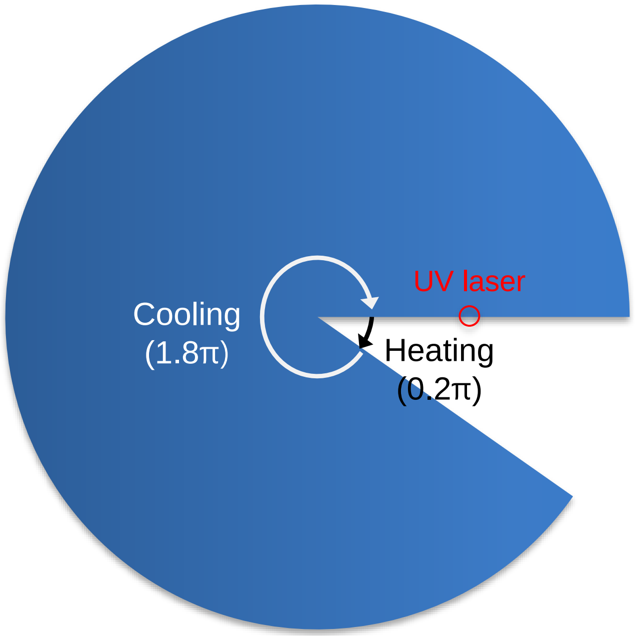
Heat load test using UV laser

❖ **Matching UV laser source power**

$$\frac{P_{UV}}{D_{UV}} * A_{UV} = I_{abs}$$

I : absorbed heat intensity @ pellicle [W/cm²]
P : source power [W]
D : beam size [cm²]
A : absorbance of pellicle membrane

Rotating slit



Parameter	Value
UV laser power specification (P_{UV})	0 – 3.0 W
Beam diameter	0.8 cm
Vacuum	~ 4 x 10^{-6} torr
On/off duty ratio (heating/cooling)	1 : 9
Rotating period	1.0 sec

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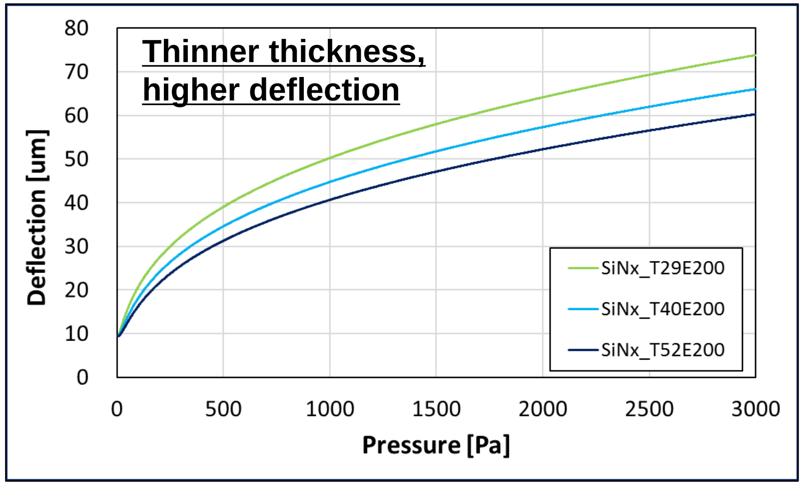
Verifying reliability of bulge test results

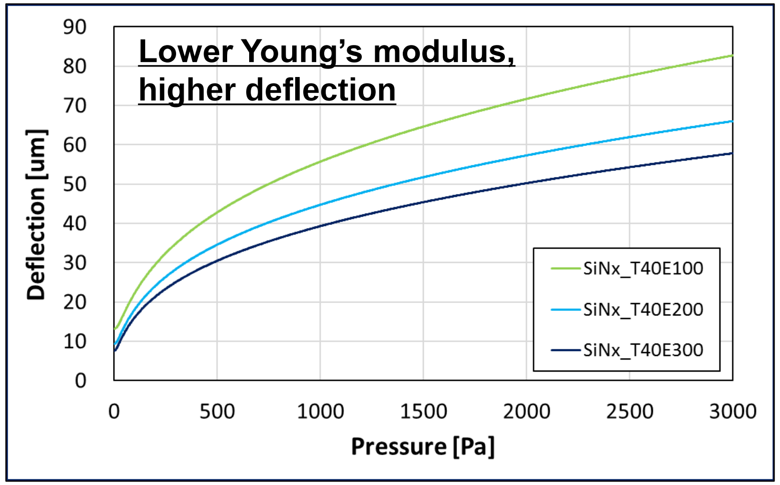
❖ **Exact solution for deflection of rectangular film**

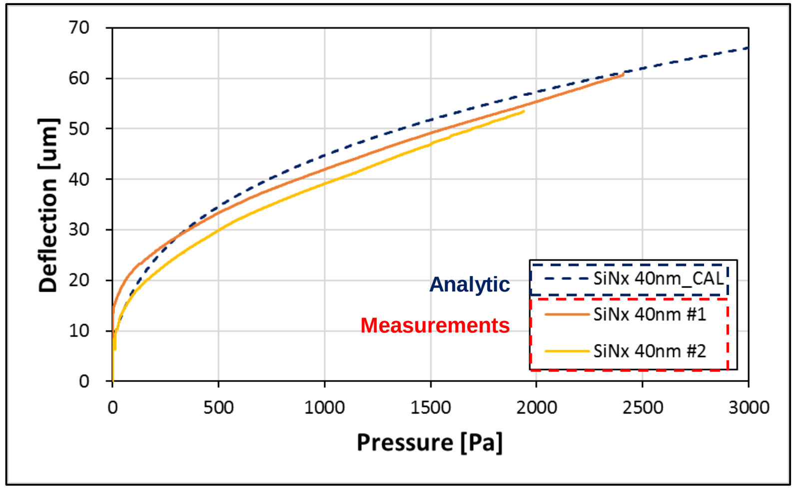
$$\Delta p = \frac{2ht}{a^2}\sigma_0 + \frac{4h^3t}{3a^4}\frac{E}{1-\nu^2}$$

a : half-width of the membrane	*t : film thickness*
p : applied gas pressure	*σ_0 : residual stress*
E : Young's modulus	*ν : Poisson's ratio*
h : deflection of membrane	*p : applied gas pressure*

Ref. A. J. Kalkman, et al, American institute of physics (1999)



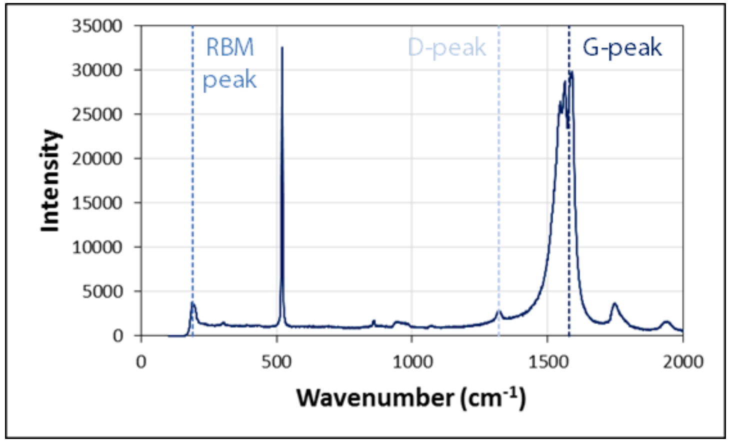


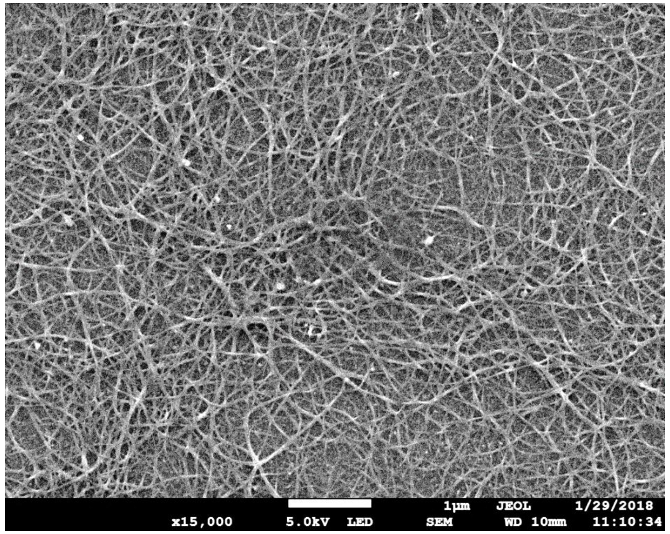


** 0.25 x 1 cm² membrane size and fixed value for the rest parameter (50 MPa residual stress)*

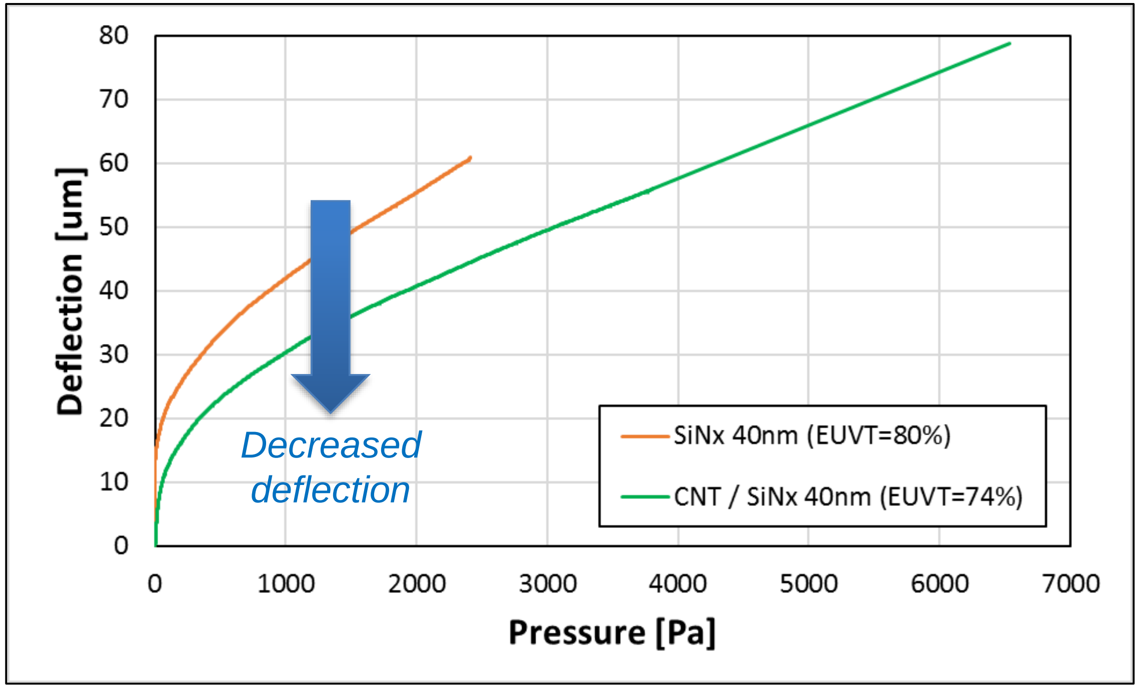
Bulge test results – CNT pellicle composite

Analysis of CNT composite pellicle





Bulge test results



- Burst pressure increased about 2.5 times with CNT layer
- Deflection depending on pressure difference was decreased as CNT layer was inserted

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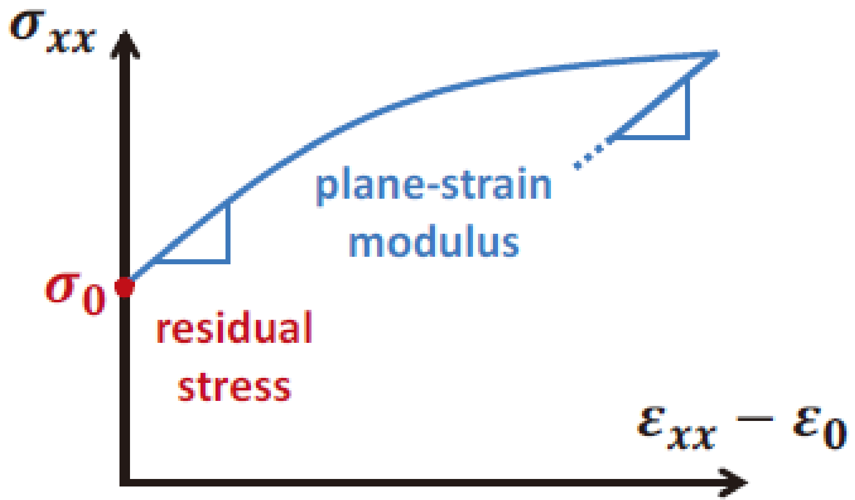
Deriving mechanical properties of CNT pellicle composite

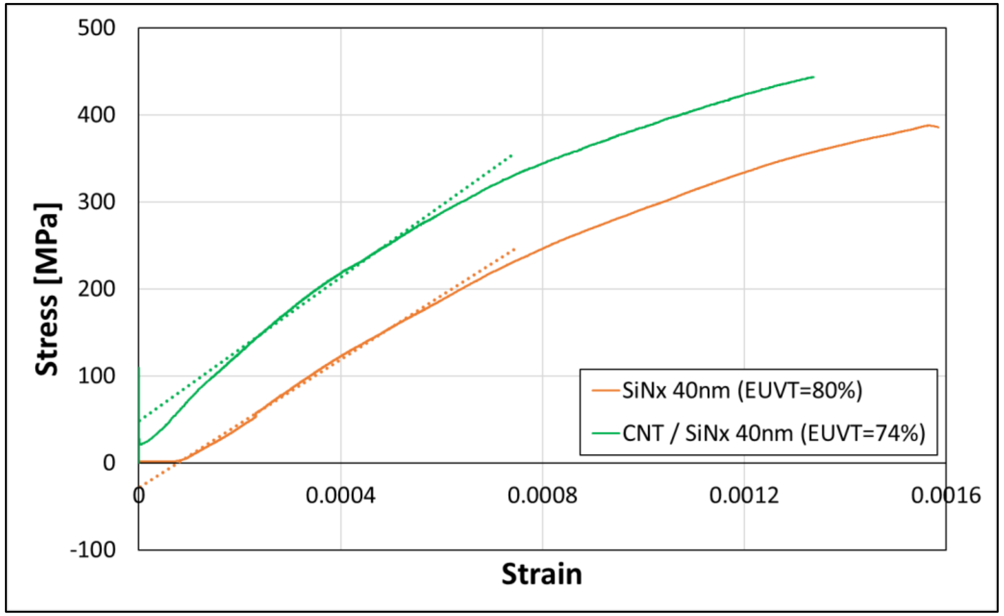
❖ Strain vs. stress curve of rectangular film

- The lateral stress and strain in the central section of the sample can be calculated from the pressure and deflection

$$\varepsilon_x = \frac{2h^2}{3a^2} + \varepsilon_0 \qquad \sigma_x = \frac{pa^2}{2ht}$$



Strain vs. stress curve



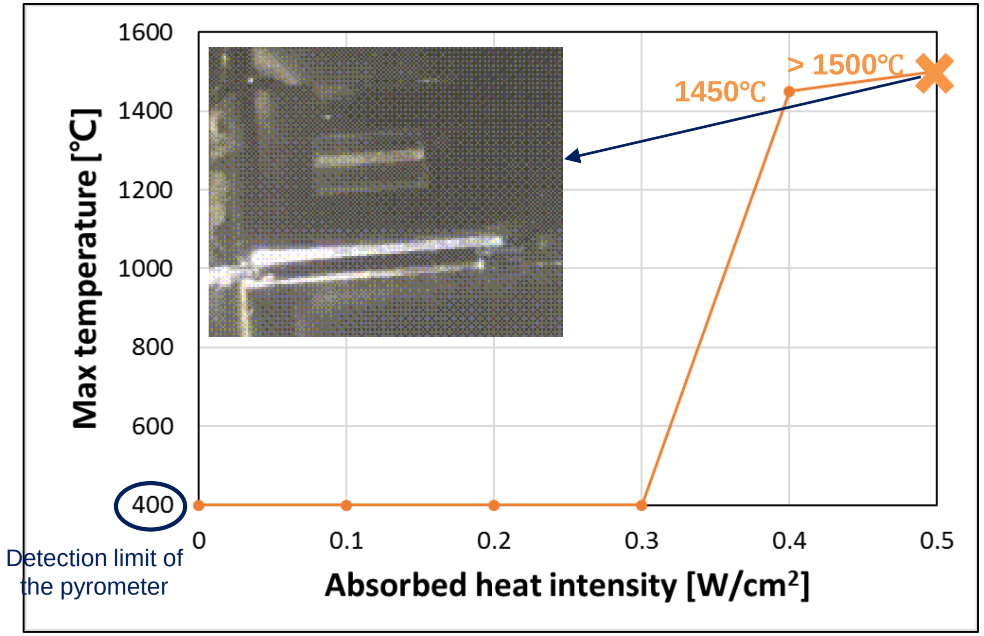
Sample	Plane-strain modulus [GPa]	Residual stress [MPa]
SiN_x 40nm	367	-28.26
CNT / SiN_x 40nm	412	48.14

Ref. Benoit Merle, "Mechanical properties of thin films studied by bulge testing" (2013)

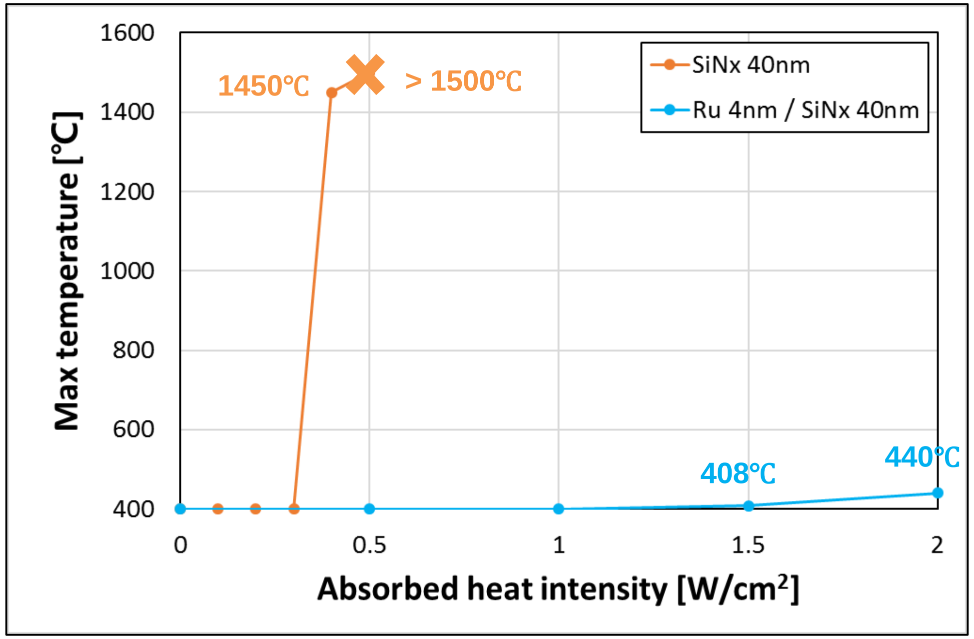
Effectiveness of thermal emission layer

❖ **Heat load test results of SiN_x based pellicle composite**

SiN_x 40nm



SiN_x 40nm vs. Ru 4nm / SiN_x 40nm



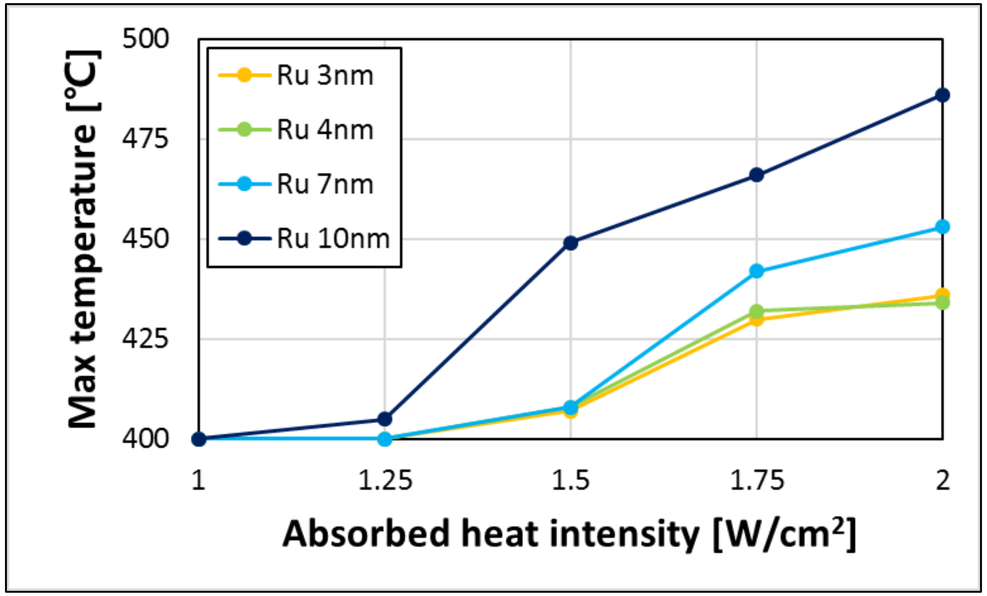
- The low thermal emissivity of SiN_x was verified by heat load test through absorbed heat intensity as the references below
- The thermal emission property of SiN_x pellicle was improved by Ru thermal emission layer

Ref. D. L. Goldfarb et al, Proc. of SPIE Vol. 9776 (2015),
P. J. van Zwol et al, J. Appl. Phy, (2013)

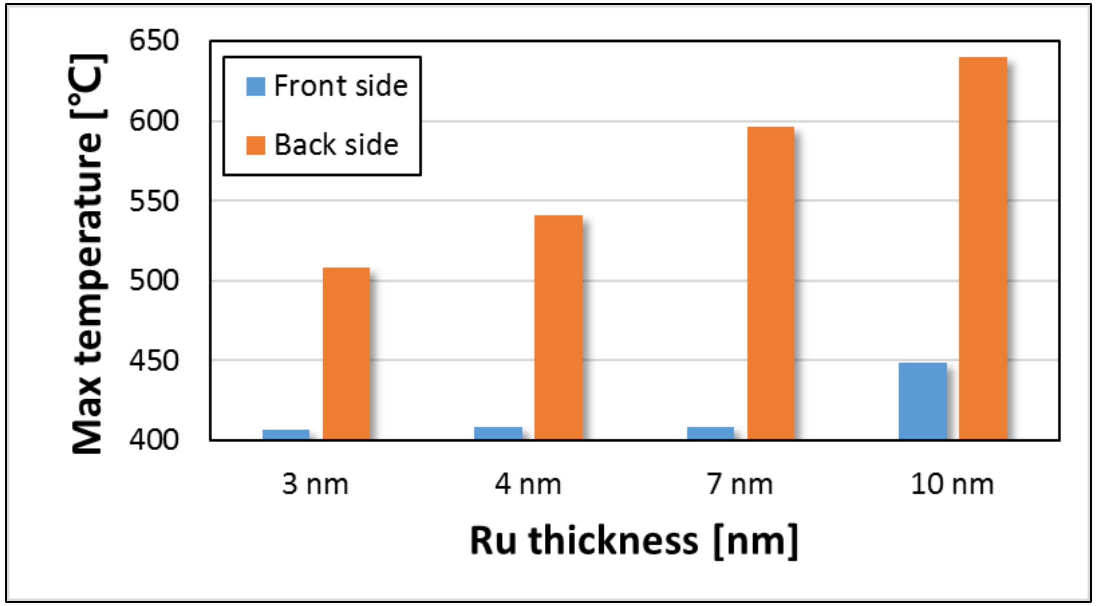
Effectiveness of thermal emission layer

❖ **Heat load test results depending on structure of pellicle membrane**

Ru / SiN_x pellicle – Ru thickness variation

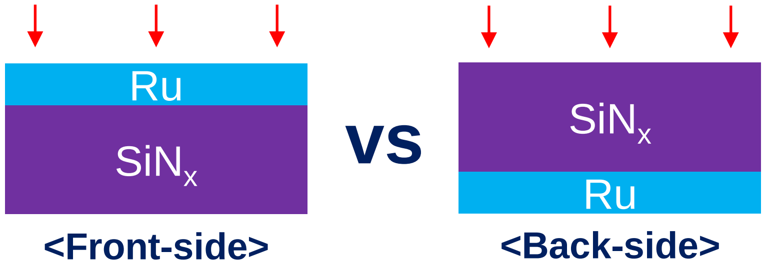


Front side vs. back side



***** Absorbed heat load per area : 1.5 W/cm^2*

- Optimum thickness of thermal emission layer was determined by heat load test depending on Ru thickness
- Heat load of the pellicle membrane could be relieved more effectively when thermal emission layer was located on incident direction (front-side)



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Verifying HVM applicability of pellicle through EUV power matching

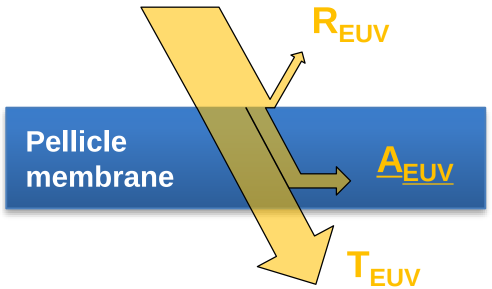
❖ **Matching UV laser source power**

Variable **Adjustable**

$$\underbrace{\phi_{EUV} * A_{EUV}}_{\text{Absorbed heat intensity by EUV source}} = \underbrace{\phi_{UV} * A_{UV}}_{\text{Absorbed heat intensity by UV laser}}$$

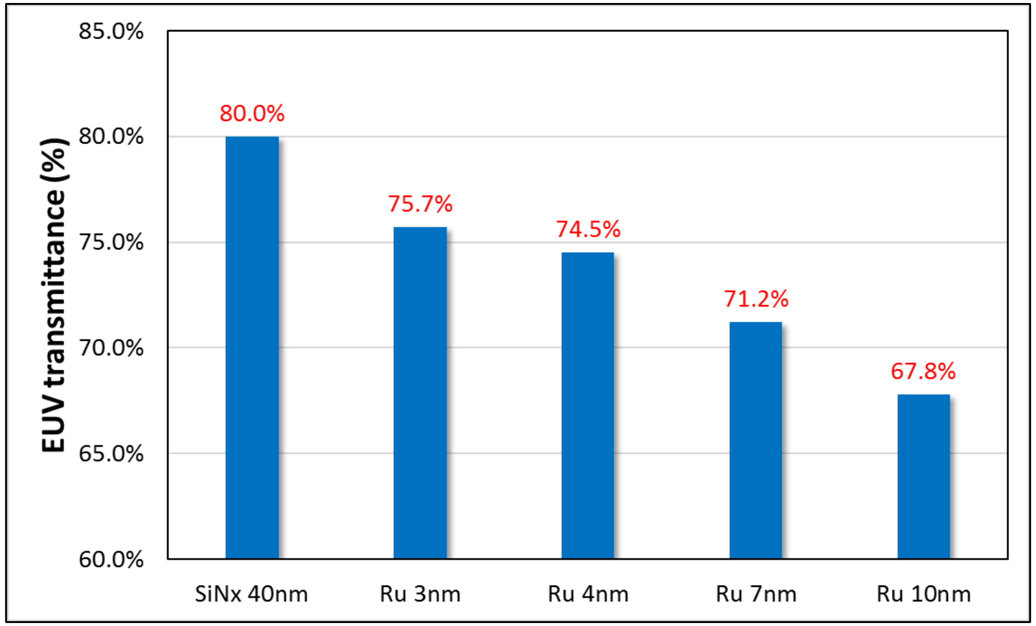
Φ : Incident heat intensity ($^{P}/_{D}$)
P : Source power [W]
D : Beam size [cm²]
A : Absorbance of pellicle membrane

Parameter		Value
Incident EUV intensity	250W	5.0 W/cm²
@ pellicle	375W	7.5 W/cm²
(ϕ_{EUV})	⋮	⋮



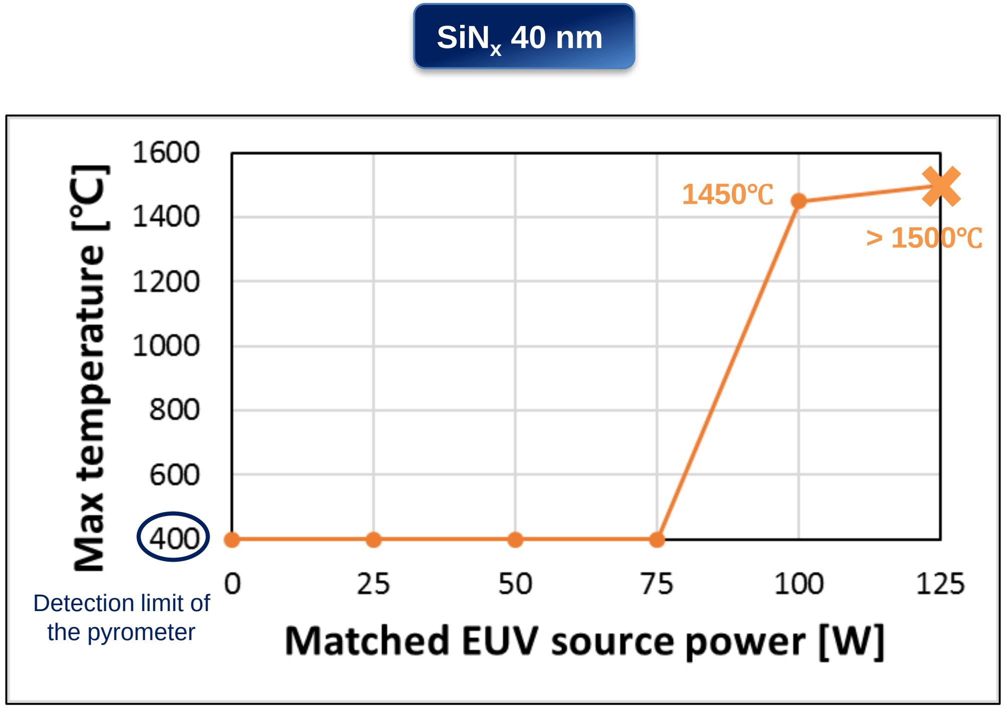
$A_{EUV} = 1 - T_{EUV}$
($R_{EUV} < 1.0\%$)

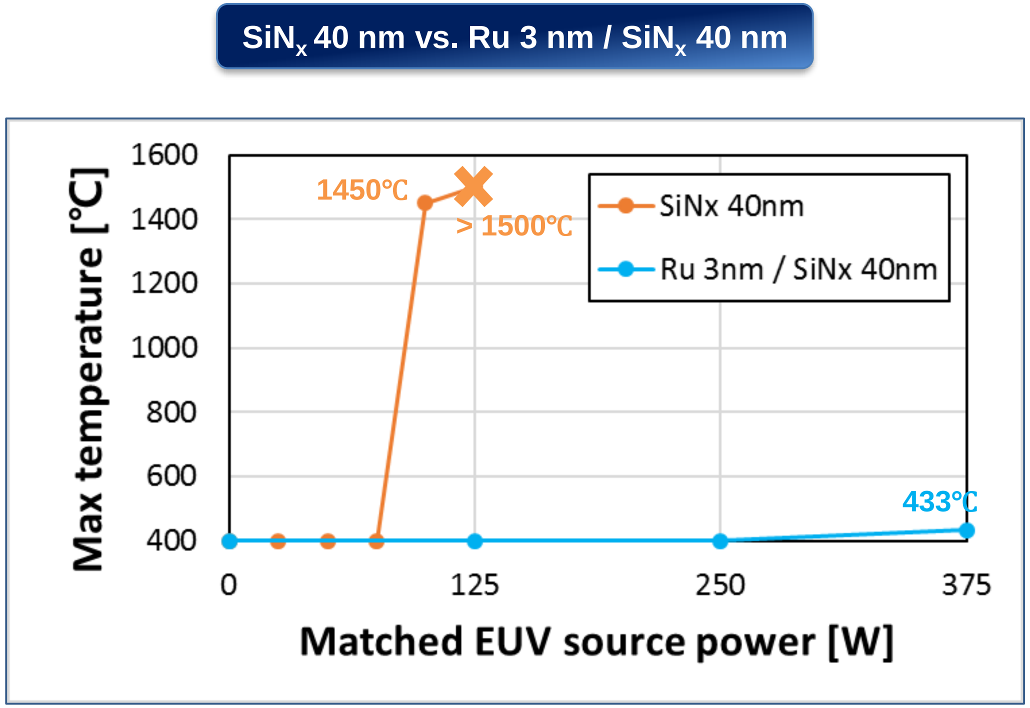
EUV transmittance (T_{EUV}) of SiN_x based composite pellicle



Verifying HVM applicability of pellicle through EUV power matching

❖ **Heat load test results**





- The HVM applicability of pellicle composite was confirmed through emulating absorbed heat intensity as the EUV source
- Pellicle composite deposited 3 nm Ru layer has excellent thermal properties when EUV source power is higher than HVM target (300W)

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Summary

- The fabrication platform of pellicle composite based on SiN_x core layer including thermal or mechanical reinforcing layer is ready

- Mechanical behavior of CNT pellicle composite was investigated by bulge-test, the mechanical properties such as plane-strain modulus and residual stress were derived

- The optimal thickness of thermal emission layer was determined

- The HVM applicability of pellicle composite including thermal emission layer was confirmed

Thank you for attentions.

Question and Answer